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Direct Numerical Simulation of a rheology model for fibre-reinforced composites

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Résumé — We present a finite element approach assisted with anisotropic mesh adaptation to model fibre-reinforced composites on compression molding processes. A single mesh embeds all the important phases (Die tool + composite material + Punching tool), implicitly described by level-set functions. A viscous transverse isotropic model for molding compression is used to take into account the influence of the fiber phase on the material response. A friction law is also added in order to described rheology data coming from the mechanical response of composites material under compression and shear tests.
Mots clés — reinforced-composites, rheology, friction, level set.

1 Introduction

Modeling fibrous materials comes together with the study of anisotropic rheology. These fibers, embedded in a thermoset matrix, enhance the mechanical properties of the composite [1]. Nowadays, glass fiber composites processed by compression molding are used as semi-structural parts since they exhibits advantageous ratios density/resistance handed with their cost-efficient processing [2]. It is of interest to understand such interaction fiber-matrix when undergoing large deformations, in order to predict composites behavior for practical applications. For reaching this point, improved models considering fiber/matrix coupling are needed. Authors in [3] have proposed a more recently viscous and transversely isotropic model fitting stress levels during experimental tests. In here, we reproduce three mechanical test : simple compression, plane strain and shear, after implementing such rheology in Rem3D. We compare the prediction of the model with the numerical results to verify its implementation. This enriching of the software with a more adapted rheology leads the application to industrial cases, where geometries are more complex. For the study cases, immersed domain are used by the assistance of level set functions.

As second point treated in this work, we present a strategy to study friction in molding compression. This technique can allow a numerical fitting of stress level, where the fitting parameter is the viscosity of a thin layer located in between the two bodies in contact.

With these studies we leave open a further investigation in more complex geometries of compression molding. Also, the availability of taking into account friction phenomena.

2 Governing equations and numerical method

In this work, we use the immerse volume approach to embeds in one mesh all the domains [4]. Air, Die, Punch and reinforced material are immersed together in an Eulerian mesh. Further, we get assisted by shapes function denominated level-sets [5], in order to differentiate the domains. These will help us along the multi-phase Stokes formulation by defining the mechanical parameters (i.e viscosity) as space function.

As stated in other works [6], multi-fluid flows can be computed by solving the heterogeneous conservation equations in $\Omega \times [0,T]$:

$$\rho \left(\frac{\partial v}{\partial t} + v \cdot \nabla v \right) - \nabla \cdot \boldsymbol{s} + \nabla p = \rho g \tag{1a}$$

$$\nabla \cdot v = 0 \tag{1b}$$

where v is the velocity field, $\boldsymbol{s}$ the stress tensor, p the pressure, ρ the density and η the viscosity, both also defined as space dependent.

For *Air and mold* we have $\boldsymbol{s} = 2\eta D$, where $2D = \nabla v + \nabla v^t$, and we set $\eta_{air} = 10^{-3}\eta_{min}^{mat}$ equal to a thousand times lower the minimum viscosity in the composite, while the viscosity of the mold is used as parameter depending on the lubrication condition to be set. The inertial terms are neglected. For the reinforced material, the extra stress tensor takes into account the fiber phase. In this work, we use the model developed in [3] which assume a homogeneous phase for fibers and paste. The stress tensor $\boldsymbol{s}$ is modified (eq.2) to take into account the fiber phase. Having,

$$\boldsymbol{s} = \boldsymbol{\sigma_s} + 2\,\eta_{eq}\mathbf{D}, \tag{2}$$

the extra stress tensor will be defined according to eq.3 and 4 :

$$\boldsymbol{\sigma}_s = 2.\underbrace{\frac{\alpha_0.K^f.D_{eq}^{m-1}}{2}}_{\eta_{eq}} \left(\alpha_1 (\boldsymbol{M} : \boldsymbol{D})\boldsymbol{M} + \frac{\alpha_2}{2}(\boldsymbol{D} \cdot \boldsymbol{M} + \boldsymbol{M} \cdot \boldsymbol{D}) \right) \tag{3}$$

$$D_{eq}^2 = \alpha_0 \left(\boldsymbol{D} : \boldsymbol{D} + \alpha_1 (\boldsymbol{M} : \boldsymbol{D})^2 + \alpha_2 (\boldsymbol{D} \cdot \boldsymbol{M} : \boldsymbol{D} \right) \tag{4}$$

$$\sigma_{eq}^2 = \frac{1}{2} \left((1+2H)\,\boldsymbol{s} : \boldsymbol{s} + (5+H-6L)(\boldsymbol{M} : \boldsymbol{s})^2 - 2(1+2H-3L)(\boldsymbol{s} \cdot \boldsymbol{M}) : \boldsymbol{s} \right) \tag{5}$$

Developped in [3], this model assumes plug flow, causing that fibers spread in-plane. The averaging of the directions modify homogeneously the macroscopic stress leading to plane isotropy. K_f states for the consistency of the matrix with the fiber phase and m states for the power-law exponent of the paste. The orthogonal direction n states for the normal to the fiber plane, here the vertical direction, and its effect is presented in the model by means of the tensor $\boldsymbol{M} = n \otimes n$. The parameters α, L, H account for fiber concentration whose correlations to find them are depicted in [3].

3 Rheological response of composite under compression and shear

The figures 1 schematizes the three rheological tests treated in this section.

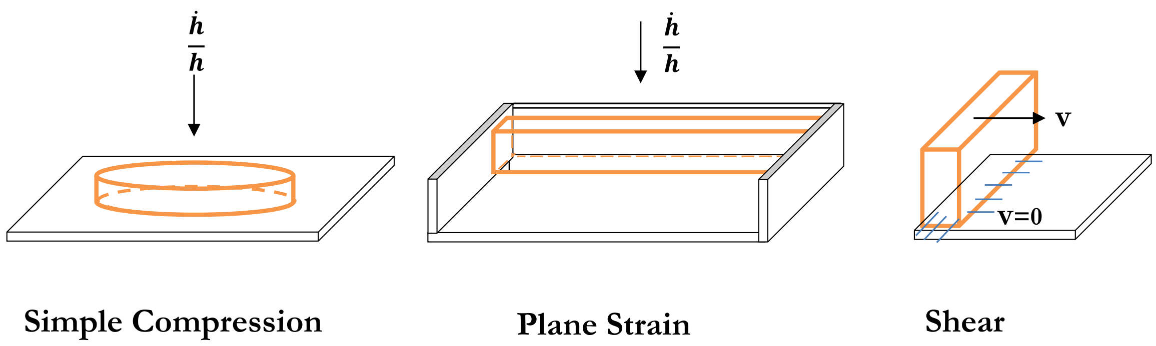

FIGURE 1 – Numerical cases : Simple compression, Plane strain and Shear.

In the case of Simple Compression, the cylinder used in this simulation has as initial values a height of 7.6 *mm*, and a radius of 12.5 *mm*, it is compressed until 4 *mm* of height (47% compression). For Plane Strain, we set a cube of 7.6 *mm* of height, width of 10 *mm* and large of 18 *mm*. it is compressed until 4 *mm*. For Shear geometry, we use the same geometry as the plane strain configuration. In the three cases, an uni-directional velocity $v = \dot{h}$ has been set, such that the strain rate $\dot{h}/h$ is kept constant during the whole deformation, and we have set three different strain rates, 10^{-4}, 10^{-2}, $1\ s^{-1}$.

The strategy of resolution used in this work for the coupling velocity-pressure-orientation is the following : firstly, the conservative equation for **velocity-pressure** is solved ; from these information, the viscosity of the non-Newtonian fluid is updated ; the new viscosity is assembled in the system and the velocity and pressure are solved again until convergence ; finally, the **transport** equation is solved for moving the level set with the converged velocity profile and the temporal scheme is moved forward.

3.1 Results

The mesh used contains 250k elements adapted to velocity and level set fields. An adaptive time step has been set to ensure the CFL condition in the flow front. The critical element is found at the boundaries of the level set. In there, we find the maximum speed in the composite v_{max} and the minimum mesh size h_{min}. Setting a CFL=0.75 we compute the time step by $\Delta t = CFL \times h_{min}/v_{max}$.

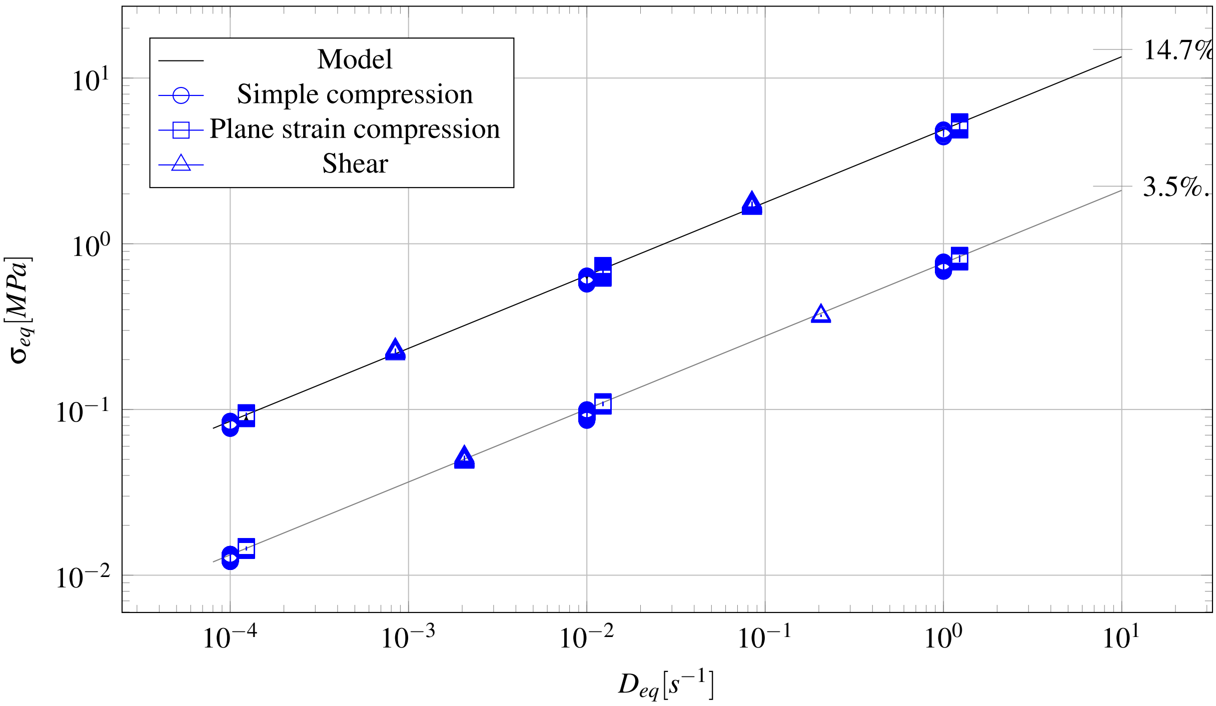

FIGURE 2 – Comparison Model [3] (straight lines) predictions for Simple Compression, Plain Strain Compression and shear for fiber volume fraction $\phi = 3.5\%$ and $\phi = 14.7\%$ at ambient temperature. Numerical Implementation in CIMLib - Rem3D.

From the results obtained, we compared the equivalent strain rate D_{eq} and the equivalent stress σ_{eq} of each deformation states, with the ones proposed for the model for the same conditions, and for two different fiber concentration of 3.5% and 14.7%. The resulting consistency of the composite for both concentration were $K^f_{3.5\%} = 0.763 MPas$ and $K^f_{14.7\%} = 4.886 MPas$. A total of 16 simulations were performed and each point of the plot is related to one full simulation under slip boundary conditions. Since the Cauchy tensor is constant in the domain, a space constant stress tensor defines the stress state.

The results presented in Fig.2 evidence the corresponding results of the software with the anisotropy model presented in previous section. We are able to reproduce the simple rheological test used to characterize the material and with this match to verified our numerical approach.

3.2 Viscous friction, an strategy for modeling friction

Friction between two bodies are related to a resistance exhibited by a body due to contact with the other body. This resistance depends on many factors as velocity, temperature, roughness and mostly a fitting equation of this phenomena is given to take this into account. In this section, we present a technique involving the appearance of a thin viscous layer. To do that, we just modified the viscosity in a small thickness between the mould and the fluid. By changing this viscosity, we can reproduce friction effect. For our study case, we use a Newtonian material of viscosity $1MPa\ s$. We solve Stokes equations. We kept the velocity constant to 5 mm/s and we plot the force to squeeze out the material. We take the two references solutions for the slip and no slip case given in [7].

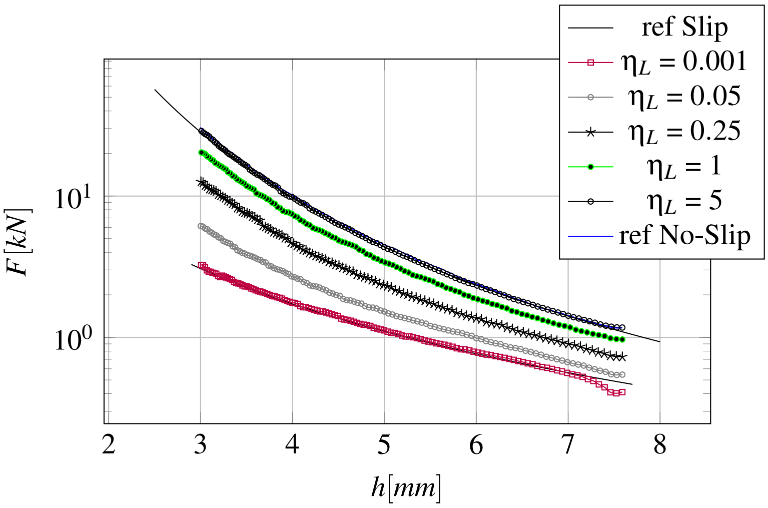

FIGURE 3 – Friction mold-Composite by means of viscosity of the contact. η_L is the viscosity of the film layer Die-Mold in $MPas$. Simulation performed in simple compression test for a Newtonian paste of $1MPas$

The forces plotted in figures 3 come directly from the integration of the numerical stresses resolution. We observe how by assigning a viscosity 10^{-3} times lower than the one of the material, we reproduce the slip case. However, by increasing the viscosity in the layer η_L, we noticed that the force needed to squeeze increases. In the case of $\eta_L = 5\eta_{mat}$ we reproduce the same no-slip condition. The intermediate ranges can be related to friction cases. The velocity profile in the extreme cases perfectly shows that we reproduce slip and no slip cases by the appearance of XZ plane velocity gradients in Y direction.

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